Global fibre reconstruction of multi-shell HARDI data

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TARGET AUDIENCE – Researchers working on tractography methods and microstructural modelling.

PURPOSE – Most common fibre tracking techniques estimate the fibre directions in all voxels and then use a local stepping method to track the entire pathway. However, the sensitivity of these techniques to local estimation errors is a well-known issue, as well as ambiguous fibre configurations arising from the symmetry of the DWI data [1,2]. Global fibre tracking methods [2–5], on the other hand, aim to reconstruct the full track configuration that best explains the data as a whole. Current methods have been limited to single-shell HARDI data and use fixed models for the fibre response function. In this study, we extend the method of Reisert et al. [3] for multi-shell HARDI data and allow to use arbitrary response functions, estimated from the data.

METHODS – *Model:* Like in [3], we model the global fibre configuration M as a set of discrete track segments and a set of connections between pairs of these segments.

Forward problem: Given the model, we simulate the MR signal D' of multiple shells in q-space using a fibre response function K_b [6] estimated from the data (as opposed to [3] that uses the well-known "stick" model on single shell data). To this end, we reconstruct the fibre ODF in every voxel as the sum of δ-functions in the spherical harmonics (SH) basis, oriented along the directions of all track segments in that voxel. Convolution of this ODF with a white matter (WM) kernel for every shell allows to evaluate the q-space signal along all gradient directions, and can be written as a matrix-vector multiplication of SH coefficients. Additionally, we introduce a second, isotropic term that models the fraction of cerebrospinal fluid (CSF) on all shells (including b=0s/mm^2). This isotropic term allows to control the relative density of track segments across all voxels. In summary, given the fibre ODF and the isotropic fraction, the simulated data of each shell equals

$$D_b{}' = K_b \otimes fODF + f_{iso}\, c_b.$$

Inverse problem: Given the DWI data D, the ultimate goal is to reconstruct the fibre configuration M as the global optimum of the forward problem. Similar to [3], we use a simulated annealing scheme to minimize the sum of an external energy term $E_{ext} = \sum \|D - D'\|_2^2$, that equals the log-likelihood of the data given the model, and an internal energy term E_{int}, that measures the prior probability of the given configuration. The internal energy depends on length and curvature of the tracks and is defined identical to [3]. The external energy, on the other hand, depends on the forward problem and is redefined as described above.

RESULTS – Data used in this work was obtained from the MGH-UCLA Human Connectome Project (HCP) database (https://ida.loni.usc.edu/login.jsp): 18 gradients at b=0s/mm^2, 3 x 90 gradients at b=1000s/mm^2, 2000s/mm^2, and 3000s/mm^2 [7], resolution subsampled to 2.5mm isotropic voxel size. The WM (fibre) response function was estimated as in [6] for each shell separately. The isotropic CSF kernel is estimated as the mean MR signal of each shell in the ventricles. The proposed method results in the set of fibre segments shown in Fig. 1 (top) and corresponding fibre ODFs overlaid on the estimated isotropic fraction (middle). For comparison, we include the fibre ODFs obtained from constrained spherical deconvolution (CSD) [5] up to SH order 10 of the b=3000s/mm^2 HARDI shell overlaid on the b0 image in the bottom figure.

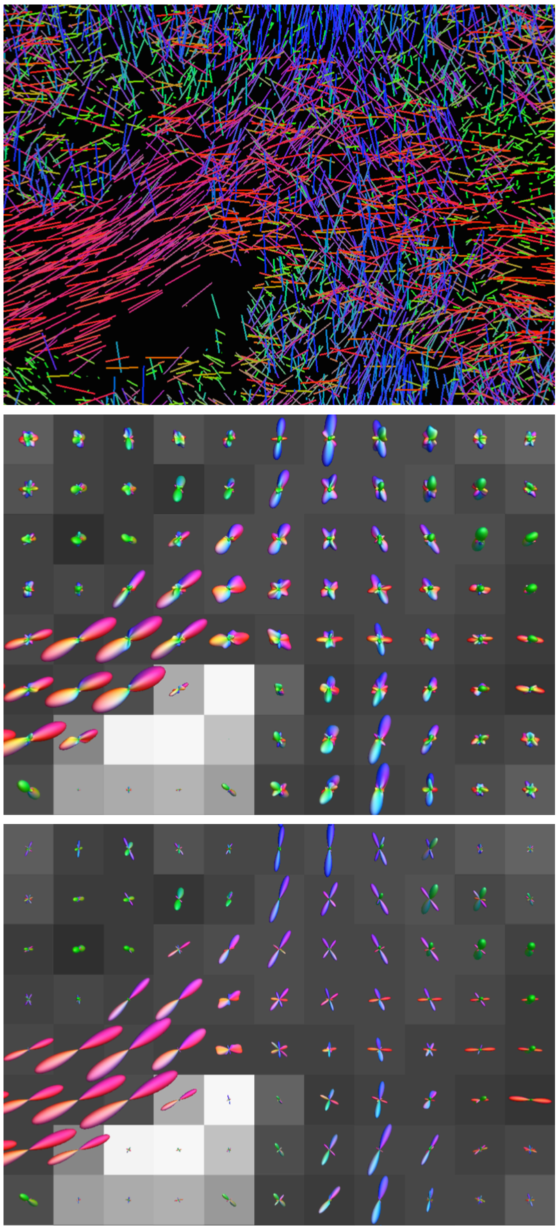

Figure 1: *Top:* coronal slab of the reconstructed track segments modelling part of the corpus callosum. *Middle:* fibre ODF reconstructed using the presented method. *Bottom:* fibre ODF of the same region, obtained from CSD [6] of shell b=3000s/mm^2.

DISCUSSION – Preliminary results show that the directions of the main WM structures are successfully recovered, although the fibre ODFs obtained from CSD appear to be more sharp. The estimated isotropic compartment correlates very well with the b0 image. Extensive parameter tuning could further improve the results, especially with respect to connectivity.

In addition, the results show that the segment density (and by extension the track density) is more or less proportional to the size of the fibre ODFs reconstructed by CSD, indicating that the fibre density is explicitly controlled by the multi-shell fibre reconstruction method. Stepping tractography methods can not generally impose this property, unless using post-processing methods like [8]. In [3] the external energy compares only the anisotropic parts of the data and hence has no control over the fibre density either. By introducing the isotropic fraction, we are able to control the density and properly deal with CSF at the same time.

CONCLUSION – The presented method can successfully recover the WM structure of multi-shell HARDI data, using *any* fibre response function represented in the SH basis. Our method paves the way towards global fibre reconstruction of more general types of DWI data.

REFERENCES – [1] Jbabdi and Johansen-Berg, *Brain Connectivity 1(3):169-183* (2011), [2] Mangin et al., *NeuroImage 80:290–296* (2013), [3] Reisert et al., *NeuroImage 54(2):955–962* (2011), [4] Fillard et al., *MICCAI 12(1):927–934* (2009), [5] Kreher et al., *Magn. Reson. Med. 60(4): 953–963* (2008), [6] Tournier et al., *NeuroImage 35(4):1459–1472* (2007), [7] Van Essen et al., *NeuroImage 62(4):2222–2231* (2012), [8] Smith et al., *NeuroImage 67:298–312* (2013).